Does too much exercise damage the heart? A narrative review of the long-term cardiovascular effects of intense training

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Abstract

Long-term exposure to high-intensity endurance exercise induces significant physiological cardiovascular remodelling. However, recent evidence suggests that prolonged exercise in athletes, particularly those exposed to decades of intensive training, may be associated with features of cardiovascular "wear and tear". These include electrical changes such as an increased risk of sinus node dysfunction and atrial fibrillation as well as structural abnormalities such as focal non-ischemic fibrosis and coronary artery calcification, more frequently observed in middle-aged and older endurance athletes. These observations support that long-term high-intensity exercise may have deleterious cardiovascular effects in susceptible individuals, although the available data are primarily derived from male Caucasian athletes. While the clinical significance of these potentially maladaptive changes at the individual level remains uncertain, at a population level high intensities and volumes of physical activity are consistently associated with reduced cardiovascular and all-cause mortality compared with sedentary behaviour, although the incremental survival benefit may plateau at very high exercise volumes. This review critically appraises the available evidence on chronic adverse cardiovascular adaptations associated with intense endurance exercise, highlighting unresolved controversies, sex- and ethnicity-related knowledge gaps, and the need to balance potential risks against the well-established survival benefits of lifelong physical activity.

Key words

Arrhythmias; Athletes, Atrial fibrillation; Coronary atherosclerosis; Exercise-induced cardiac remodelling; Myocardial fibrosis; Sports cardiology

Central figure

1. Introduction

Regular physical exercise is widely recognized as one of the most effective strategies to promote health and prevent diseases [1]. Its benefits extend well beyond the cardiovascular system, positively influencing metabolic profile, mental health, musculoskeletal function, and overall longevity [2–6]. Accordingly, international guidelines consistently recommend regular physical activity as a cornerstone of primary and secondary prevention[7–10].

However, some people engage in high intensity and high volume recreational exercise, significantly exceeding guideline recommendations. In recent decades, participation in competitive and non-competitive endurance sports has also markedly increased, leading to a growing population of athletes who train for several hours per week[11]. Of particular interest is the group of so-called "master athletes" (≥35 year-old according to current guidelines[12]): middle-aged or older individuals who often practice individual endurance disciplines such as running or

cycling, with training intensities and volumes that may approach those of professional athletes[13]. As already suggested by Paracelsus more than 500 years ago, "the dose makes the poison". Therefore, as these extreme levels of sport exposure emerge in society, a question has emerged: can excessive exercise regimes lead to deleterious effects to the cardiovascular system?[8,14–16] The aim of this review is to examine the available evidence on the possible association between intense and prolonged exercise training and cardiovascular abnormalities, focusing on both electrical and structural findings, to help distinguish between commonly held beliefs and evidence-based conclusions and to discuss the clinical implications.

2. Writing methodology

This narrative review was independently developed by members of the Sports Cardiology Nucleus of the European Association of Preventive Cardiology with complementary expertise in electrophysiology, cardiac imaging, inherited heart diseases and exercise physiology. An initial outline was shared among all authors, after which the two coordinators assigned individual sections to pairs of authors according to their expertise. For each section, the responsible authors selected the most relevant literature, prioritizing large cohort studies published within the last 10 years and systematic reviews. The complete draft and reference list were subsequently reviewed by all co-authors in two revision rounds, allowing additional relevant studies to be suggested and incorporated. This approach is consistent with the methodology of a narrative review.

3. Review of evidence: Electrical changes

3.1 Sinus bradycardia / AV block

Sinus bradycardia (SB) is a well established physiological finding among athletes, occurring in up to 85% of all athletes, exceeding 90% of endurance athletes. It is often accompanied by sinus pauses, ectopic atrial rhythm, junctional rhythm, and atrioventricular (AV) conduction anomalies. Profound SB (<40 bpm) occurs in approximately 4% of athletes, with extreme bradycardia (<30 bpm) reported in few asymptomatic endurance athletes[17–21]. First-degree AV block and Mobitz I second-degree AV block are also often registered during rest or sleep, and tend to normalize with exercise. In contrast, marked PR prolongation (>400 ms) or high grade AV block are considered pathological and may be associated with metabolic, autoimmune, infectious, or genetic cardiac diseases[17–21].

Traditionally, SB and AV block in athletes were attributed to increased vagal tone and thought to be reversible after detraining [22]. However, recent experimental data obtained from animal models suggest that exercise may cause intrinsic modification of the sinus node and AV node function, through downregulation of ion channels (such as the HCN4) involved in impulse generation and conduction[23]. This hypothesis is supported by the observation that dual pharmacological blockade (beta blockers plus atropine) does not completely reverse sinus bradycardia in athletes[24–26]. At variance with extrinsic (vagal) modulation, these intrinsic (epigenetic) modifications may not be completely reversible after cessation of the athletic career and predispose former athletes to clinically relevant bradycardia later in life[27].

From a clinical point of view, some studies suggest that most former elite athletes continue to experience bradycardia, even after detraining, and that individuals with a history of endurance sport are also more likely to receive a pacemaker due to idiopathic bradyarrhythmias (i.e. in the absence of structural heart disease) at a younger age than non-athletes[19,28–30]. A large Swedish study observed that male cross-country skiers, especially those with the highest training levels,

had higher rates of bradycardia and pacemaker implantation than non-skiers. Interestingly, no associations were found among female skiers, and mortality rates did not differ between male skiers with and without a pacemaker[31].

These findings suggest that high-intensity and volume endurance exercise may accelerate sinus or AV node dysfunction over time, through intrinsic changes in nodal cells (ion-channel downregulation) possibly in combination with genetic predisposition and/or stress-induced fibrosis of the SA or AV node [23]. Although these arrhythmias appear to infer a more complex picture, beyond physiologically driven adaptation, they affect only a small subset of athletes and do not seem to have any negative impact on long-term survival.

3.2 Atrial fibrillation

Moderate physical activity has been shown to reduce the risk of developing atrial fibrillation (AF) in the general population [32]. Endurance sports, however, appear to be a risk factor for AF, with a 10-fold increased risk quoted in some studies when compared to sedentary individuals[33]. This association is well-established in master male endurance athletes (>40 years) [12,34–40] with a dose-response U-shape pattern [41,10,27], independent of traditional cardiovascular risk factors. Data on female athletes are scarce and contradictory, suggesting possible sex-specific remodeling patterns[42–45]. These observations should, however, be interpreted with caution, as females are generally underrepresented in athletic cohorts. Interestingly, longitudinal studies showed that, despite the increased prevalence of AF, former athletes showed a lower incidence of stroke than nonathletes[38,43].

Several mechanisms have been implicated in the development of AF in athletes. Originally, AF in athletes was linked to left atrial dilation (LA) that is a typical feature of the athlete's heart. Left

atrial dilatation is a risk factor for AF in the general population as it is associated with increased wedge pressure and atrial fibrosis [46]. However, LA dilation in athletes without AF is a physiological response to increased volume load and is usually not associated with impaired indexes of atrial function suggesting atrial myopathy [46,47]. In master athletes with AF, LA end-systolic volume is similar to athletes without AF; on the other hand, LA function quantified by emptying fraction, expansion index, reservoir and contractile strain is worse[47]. These findings indicate that LA dilation does not per se increase the risk of AF as long as functional indexes are preserved. Atrial dysfunction suggests an underlying atrial myopathy, potentially caused by the stress of prolonged exercise and characterized by chronic inflammation and fibrosis acting as key substrates for arrhythmogenesis[48–51]. High vagal tone, typical of athletes, may also lead to an increased propensity to AF as it decreases the atrial refractory period [52]. Premature atrial beats originating from the pulmonary veins often trigger AF but there is no evidence that endurance sport increases the atrial ectopic burden[53,54]. Finally, changes in calcium currents, ion channels and gap junctions can lead to modifications of electrophysiological characteristics of atrial myocytes independently from LA structural remodelling[55,56].

Detraining may partially reverse some of the structural and functional adaptations that are thought to trigger AF in athletes, which is why endurance athletes with paroxysmal AF may be advised to reduce their training intensity and volume[32]. A blanket, one-size-fits-all approach is, however, not justified. A shared-decision model is warranted, incorporating symptom burden, sporting discipline, treatment options (rhythm versus rate control strategies), and the presence of underlying structural heart disease. Athletes with AF requiring anticoagulation should avoid collision or body contact sports[57]. Definitive long-term human studies on reversibility remain lacking[58], hence why guidelines on exercise prescription in AF continue to rely heavily on expert consensus.

3.3 Premature ventricular beats

The relationship between physical activity and premature ventricular beats (PVBs) remains a matter of debate. The few studies that have investigated the acute effects of exercise on ventricular arrhythmic burden have reported inconsistent results. Two studies conducted in athletes completing a marathon did not demonstrate any significant effect on ventricular arrhythmias[59,60] whereas a study performed during an ultramarathon observed a slight increase in the number of individuals presenting at least one PVB on a 1-minute ECG recorded before and after the race[61]. However, the more clinically relevant question is whether long-term training leads to a chronic increase in ventricular arrhythmic burden. This issue has important clinical implications since demonstrating a higher PVB burden with exercise could potentially downplay the diagnostic significance of such a finding in athletes.

Two recent studies have shown that, on average, athletes exhibit a relatively low burden of PVBs. The first study enrolled non-elite volunteer athletes of different ages and compared them with sedentary controls. It reported that 24-hour holter monitoring identified a low frequency of PVBs (6% had >100 PVBs/24hrs) and non-sustained ventricular tachycardia (NSVT) (2%), similar to sedentary controls. Notably, 80% of athletes with frequent PVBs showed infundibular (left bundle branch block/inferior axis pattern of the ectopic QRS pattern) or fascicular morphologies[62]: commonly observed PVB morphologies that are rarely associated with underlying structural heart disease[63]. The likelihood of frequent (>100 PVBs/24hrs) or repetitive PVBs increased with age, but was not related to gender or training intensity/volume [62]. The second study recruited 296 highly trained young elite athletes and 138 endurance master athletes (mean age 56 years) in the pro@heart and master@heart registries. Most athletes had a low PVB

burden over a 24-hour period (median 1 PVB/day in young elite athletes and 6 PVB/day in middle-aged athletes). Only a minority of athletes exhibited >100 PVBs/24 hours or NSVT, with a significantly higher prevalence among middle-aged athletes (13% and 8%, respectively) compared with younger athletes (5% and 2%, respectively) and middle-aged non-athletes (6% and 2%, respectively)[64]. Another study from the same group suggested that men athletes exhibited a higher prevalence of NSVT compared to female athletes (11% versus 2%), although the median number of PVBs was similar between sexes (3.2/day versus 1.4/day)[65]. In summary, these studies suggest that frequent and repetitive PVBs are observed only in a minority of athletes and to what extent exercise directly contributes to the development of ventricular arrhythmias remains unclear. A recent study suggested that PVBs in athletes with structurally normal hearts may also be attributed to underlying metabolic (example iron deficiency) or inflammatory states [66].

Another knowledge gap is the impact of detraining on ventricular arrhythmic burden. More than 20 years ago, Biffi et al. observed that detraining significantly reduced the number of PVBs in athletes with frequent PVBs and structurally normal hearts[67]. However, the interpretation of these findings is limited by the selection of athletes with frequent ectopy at baseline and the possibility that spontaneous variability or regression to the mean may have contributed to the observed reduction. The same group however reported that resuming physical activity was not associated with recurrence of PVBs [68]. Another study conducted in non-elite athletes demonstrated a spontaneous variability of PVB burden over time, regardless of whether athletes continued training or not [69]. More recently, Di Gioia et al. evaluated a cohort of 109 athletes with frequent PVBs and normal cardiac magnetic resonance imaging (MRI) over a mean follow-up of 3 years. In 40% of these athletes, ventricular arrhythmias resolved despite ongoing training.

Notably, in 2 of 67 athletes with persistent PVBs, repeat MRI revealed the development of structural heart disease [70]. In conclusion, although detraining may be associated with a reduction in ventricular arrhythmic burden in some athletes, a clear cause–effect relationship has not yet been established [71].

3.4 Exercise-induced long-QT syndrome

The QT interval on the surface electrocardiogram reflects the duration of ventricular depolarization and repolarization and results from the complex interplay between inward depolarizing currents, mainly mediated by sodium and calcium channels, and outward repolarizing potassium currents. QT prolongation may occur as a consequence of genetic conditions, such as congenital long QT syndrome, or as an acquired phenomenon, commonly driven by electrolyte disturbances, drugs, or systemic conditions[72]. In athletes, as in the general population, heart rate–corrected QT (QTc) is on average longer in females[73,74]. When average QTc was compared between athletes and nonathletes, studies showed mixed results with some reporting slightly higher values in athletes and others showing no differences[75–78]. In addition, the use of the Bazzett method of correction may become less accurate in athletes with bradycardia, hampering the comparison with sedentary individuals usually showing higher heart rates[79]. However, the extent to which QTc prolongation reported in athletic cohorts reflects the correction formula rather than true repolarization changes remains uncertain.

There is some evidence that a small minority of athletes may develop marked QTc prolongation because of intense training: the so-called “exercise-induced long-QT syndrome”. In a cohort of 2000 asymptomatic elite mixed and endurance athletes who underwent a 12-lead ECG and an echocardiogram, the prevalence of prolonged QT was only 0.4%. However, none of the athletes

with a QTc between 460 and 500 ms exhibited a disease-causing genetic variant or had a first-degree relative with long QT syndrome, suggesting a possible effect of the exercise in such slight QT-interval prolongation[80]. One of the key studies supporting the hypothesis of a possible "exercise-induced long QT" involved 310 competitive athletes referred for suspected long QT, in whom QT intervals normalized after a period of detraining in a subset of asymptomatic individuals with negative genetic testing and no family history[81]. Other investigations confirmed that long QT in athletes with negative genetic testing/family history usually resolve with detraining[82]

Several mechanisms have been proposed to explain this presumed exercise-induced QT prolongation phenomenon. These include delayed ventricular repolarization related to increased left ventricular mass and chronic mechanical stretch. Specifically, chronic exposure to increased hemodynamic load during intensive training has been suggested to influence ventricular repolarization via mechano-sensitive pathways, including the upregulation of stretch-activated sarcolemmal Ca^{2+} channels[80,81,83,84].

In conclusion, a significant QT prolongation that normalizes after detraining may occur in a small minority of athletes. It is not known if the arrhythmic risk of the "exercise-induced long QT" is lower than that of congenital long QT caused by gene mutations and therefore the management of these athletes remains equivocal.

Table 1 and figure 1 summarizes the available evidence on the relationship between prolonged intense training and adverse structural remodelling as well as response to detraining.

4. Review of evidence: structural abnormalities and troponin release

4.1 Exercise-induced arrhythmogenic cardiomyopathy phenotype

An expanding body of clinical, imaging, molecular, and electrophysiological evidence supports the concept that chronic, high-intensity endurance exercise can promote disease penetrance in desmosomal-gene mutation carriers and worsen the phenotype in patients with arrhythmogenic right ventricular (RV) cardiomyopathy[85–88]. However, a minority of athletes may exhibit RV abnormalities extending beyond the expected spectrum of physiological exercise adaptation, including disproportionate RV dysfunction and complex ventricular arrhythmias, even in the absence of pathological variants or familial disease[89]. Based on these observations, the term 'exercise-induced arrhythmogenic right ventricular cardiomyopathy (ExI-ACM)' has been proposed to describe a potentially maladaptive and arrhythmogenic phenotype at the extreme end of the athletic RV remodeling spectrum [90,91], although its precise prevalence and even its definition as a distinct disease entity remains debated[92].

The hypothetical pathophysiological basis for ExI-ACM rests on the uniquely high wall stress imposed on the thin-walled RV during sustained endurance exercise [93]. Because pulmonary vascular resistance decreases far less than systemic resistance during exertion, the RV experiences disproportionately elevated afterload and mechanical strain. Over time, this may exceed the myocardium's "desmosomal reserve," leading to progressive microstructural disruption of cardiomyocyte junctions [87,94]. In addition to mechanical overload, prolonged high-intensity exercise may activate myocardial inflammatory pathways and promote autoimmune responses directed against desmosomal proteins, thereby weakening intercellular coupling and increasing susceptibility to electrical instability[91]. This mechanistic framework provides a plausible

explanation for why arrhythmogenic phenotypes may arise even in athletes without desmosomal gene variants and why the condition appears to cluster in individuals with long-standing, high-intensity training histories [95,96]. However, a strong individual predisposition possibly related to still unknown genetic background is needed to develop ExI-ACM, as in the vast majority of athletes with a long history of intense sports activity no signs of RV cardiomyopathy can be found [97,98] (Figure 2). Importantly, physiological RV and right atrial enlargement are common findings in endurance athletes and, in isolation, should not be considered evidence of cardiomyopathy.

Clinically, the proposed ExI-ACM phenotype is primarily characterized by complex ventricular arrhythmias, typically occurring in the setting of subtle, disproportionate, or functionally abnormal RV remodeling rather than isolated chamber enlargement alone and in the absence of desmosomal gene mutations[89]. These arrhythmias frequently exhibit a right ventricular outflow tract (RVOT) morphology, which is traditionally regarded as a benign entity in otherwise healthy young individuals[18,99,100]. In athletes, however, distinguishing truly benign RVOT ectopy from an early arrhythmogenic cardiomyopathy requires careful contextual evaluation. Resting structural cardiac evaluations may reveal subtle findings that can overlap with physiological athletic remodeling, including mildly asymmetric RV enlargement or borderline reductions in RV strain, and no detectable fibrosis on MRI[101,102]. Regional wall-motion abnormalities, characteristic of established familial ARVC, are uncommon in early exercise-associated remodelling, further blurring diagnostic boundaries[101]. However, exercise echocardiography and exercise MRI can uncover impaired RV contractile reserve, stress-induced dilation, or functional deterioration not evident at rest[101], underscoring the potential of stress-integrated imaging to identify early pathological remodelling before overt structural changes become apparent. Finally, electrophysiological study with endocardial voltage mapping may be indicated in athletes with persistent symptomatic and

complex RVOT-type ventricular arrhythmias combined with no or subtle imaging abnormalities, as patchy regions of abnormal myocardial voltage on electro-anatomical mapping, indicating early arrhythmogenic substrate below the resolution of conventional imaging, may be revealed[103–105].

In athletes with clinically significant ventricular arrhythmias and suspected arrhythmogenic RV remodeling, exercise restriction remains a central management strategy as detraining reduces arrhythmic risk in both genetic and gene-elusive arrhythmogenic cardiomyopathies, however complete resolution of structural abnormalities is not typically observed[88,95].

4.2 Isolated non-ischemic left ventricular scar

MRI is the reference modality for identifying ischemic and non-ischemic myocardial fibrosis, through late gadolinium enhancement (LGE) imaging and parametric mapping techniques.

In athletic populations, an increased prevalence of non-ischaemic LGE has been reported, particularly among master athletes. Although prevalence rates vary across studies, they are higher than in sedentary controls, particularly among older athletes and those with many years of high-intensity endurance training [27,64,106,107]. Several cohorts report a LGE prevalence between 12% and 35%, particularly among long-distance runners, triathletes, and cyclists[64,108–110]. Some studies of master athletes who practice endurance sports describe even higher rates, approaching 50%[107,108,111], but frequently involving RV insertion points and, less commonly, ischaemic-type scars[112]. Inferior RV hinge point LGE refers to focal myocardial fibrosis detected by cardiac MRI at the insertion points between the right ventricular free wall and the interventricular septum, often associated with increased mechanical stress. Hinge point LGE has been reported as a frequent

finding in athletes and is not associated with ventricular arrhythmias or adverse outcomes[113]. Other studies do not show a significant difference between athletes and controls[114,115], underscoring the influence of age, training regimen and exposure, and methodological variability (i.e. MRI technique and interpretation) on prevalence estimates[116]. Notably, no increased diffuse fibrosis has been reported in master athletes compared to controls using T1 mapping techniques[117–120]. In some studies, the presence of LGE has also been associated with a higher prevalence of ventricular arrhythmias, supporting the concept that fibrotic areas may serve as arrhythmogenic substrates in susceptible individuals[64,107,111,121,122]. Overall, MRI studies indicate that non-ischaemic LV fibrosis is not rare in well-trained athletes, but a direct causal association between sport and fibrosis has not been demonstrated.

Two leading aetiological mechanisms have been proposed to explain these MRI findings. One hypothesis suggests that a proportion of fibrosis represents residual scar from prior clinically overt or subclinical myocarditis. This is supported by the observation that many LGE patterns in athletes, particularly subepicardial or mid-wall enhancement, mirror those typically seen following viral myocarditis. Given the exposure of athletes to viral illness and the possibility of continuing training during minor illness, silent or incompletely recognised myocarditis remains a biologically plausible contributor. In this context, persistence of scar tissue despite clinical recovery may explain focal non-ischaemic fibrosis detected in otherwise asymptomatic athletes[116,122,123]. The second hypothesis relates to repetitive haemodynamic loading and mechanical myocardial stress associated with chronic high-intensity endurance training[106]. Sustained exposure to increased preload and afterload, repetitive ventricular wall stress, and pressure-volume fluctuations may trigger repeated micro-injury, focal myocyte necrosis, and subsequent replacement fibrosis. This mechanism is particularly relevant to hinge-point fibrosis, occurring where mechanical stress is

greatest[113]. Furthermore, prolonged endurance exposure has been associated in some studies with transient biomarker elevation, temporary ventricular dysfunction, atrial and ventricular remodelling, and in certain cases, ventricular arrhythmias and reduced systolic function, as highlighted in more recent endurance athlete cohorts [64,107,124]. It is likely that both mechanisms coexist, influenced by age, genetic predisposition, inflammatory susceptibility, training intensity, and cumulative lifetime exercise exposure. Finally, in a minority of cases non-ischemic LGE can be the hallmark of an underlying genetic cardiomyopathy with predominant LV involvement. According to a recent study evaluating 40 athletes with non-ischemic LGE and ventricular arrhythmias who underwent systematic genetic testing and family screening, 7 showed pathological gene mutations and 2 recurrent familial disease in the absence of identified gene mutations[122].

Continued prospective evaluation is required to clarify causality, prognostic implications, and stratification strategies to differentiate benign adaptive findings from early pathological change in the athletic heart.

4.3 Coronary artery disease

Coronary atherosclerosis, measured by coronary artery calcification scores (CACS), is strongly linked to adverse cardiovascular outcomes [125]. Unexpectedly, multiple independent international cohorts reported increased CACS and atherosclerotic plaque prevalence in middle-aged and older male athletes in comparison to their less active peers[126–130]. In 2008, Mohlenkamp et al. first reported higher CACS in male marathon runners compared to age- and risk factor-matched individuals from the general population (the Heinz Nixdorf recall study)[128]. This was initially

presumed to be (partially) explained by a large proportion of (ex-)smokers among the marathon runners. However, subsequent studies confirmed the higher prevalence of CACS and atherosclerotic plaques in male athletes compared to non-athletes[127], and an association between the prevalence of CACS, atherosclerotic plaque and lifelong exercise volume[126]. Larger general population studies have also shown increased CACS in individuals engaging in greater exercise volumes[129]. The impact of exercise intensity versus exercise duration is not yet clear, since the MARC-2 study reported an association between higher proportion of very vigorous intensity exercise and more progression of CACS[131], whereas a cross-sectional analysis from the Cooper Clinic Longitudinal Study showed more CACS with longer duration of exercise, but less CACS with higher exercise intensity[132] . A subsequent longitudinal analysis of the Cooper Clinic found no association between physical activity volume and progression of CAC[133], in line with findings from the MARC-2. Exercise volume thus appears to be associated with CAC prevalence and not progression.

Interestingly, exercise characteristics were not related with coronary atherosclerosis in female athletes [134]. The explanation for this difference between men and women is not clear, but may relate to the previous protection of estrogen and the relatively low burden of atherosclerosis in women, or due to sex-specific hemodynamic or inflammatory factors.

Early studies involving male athletes reported a higher prevalence of calcified plaques and a lower prevalence of mixed morphology plaques in the most active individuals[126,127]. These observations, coupled with lower mortality in athletes, led to the hypothesis that increased CACS in athletes might indicate accelerated calcification and plaque stabilization, similar to the effect of statins[135]. Unfortunately, the Master@Heart study found no differences in plaque morphology between lifelong male endurance athletes and controls. It is worth noting that the controls were

allowed to engage in up to 3 hours of exercise per week and were physically fit (122% of estimated VO2max). Additionally, both groups had predominantly calcified plaques and only few of the athletes exhibited plaques with high vulnerability characteristics (defined as at least 2 high risk features: low attenuation, spotty calcification, positive remodelling, or napkin-ring sign, which are associated with a higher coronary event risk)[136]. This suggests a less detrimental plaque morphology in all groups. The lack of difference may therefore be explained by the high fitness status and associated coronary plaque remodeling of the control group[130]. Future studies should further focus on the association between exercise characteristics and plaque characteristics, including high-risk plaque features and coronary inflammation as this may importantly impact the risk associated with coronary plaques[136].

The mechanisms underlying increased coronary atherosclerosis in male athletes are not yet elucidated. Traditional cardiovascular risk factors such as smoking, hypertension and a genetic component as indicated by a family history of coronary heart disease, but also lipoprotein(a) values, are important predictors of coronary atherosclerosis in athletes[137,138], but do not explain the degree of atherosclerosis observed. Exercise-related factors such as sustained increases in blood pressure and heart rate, mechanical stress, disrupted laminar flow, and exercise-induced inflammation are potential contributors [139]. Exercise-induced changes in lipid metabolism and calcium homeostasis, along with an atherogenic diet and genetic factors may also contribute[140]. Future studies are needed to investigate the role of these proposed mechanisms. It is recommended that risk factors are adequately managed in athletes, according to general population guidelines[39].

Outcome data in athletes with coronary atherosclerosis is limited. A recent follow-up study from the American Cooper Clinical Longitudinal Study showed that individuals with the highest

exercise volume (>3000 Metabolic equivalent of Task [MET]-min/week) had the lowest risk for all-cause mortality, but interestingly found that these individuals with the highest exercise volume had a similar risk for myocardial infarction and revascularization as the individuals with low exercise volume (<500 MET-min/week)[141]. The individuals with a moderate exercise volume (500-3000 MET-min/week) had the lowest risk of myocardial infarction and revascularization. Importantly, the association between CACS and increased CV risk was independent of exercise volume, suggesting that the most active individuals are not protected from the health risks of increased CACS. Similarly, data from the same cohort previously showed an increased risk of adverse outcomes among the fittest individuals with high CACS versus without CACS, although higher cardiovascular fitness was associated to lower the risk of cardiovascular events independently of CAC[142].

Based on current studies, there is no evidence that reducing exercise intensity would slow the progression of CAC or lower the incidence of CV events. It is however important for athletes to consider that exceedingly high exercise volumes will not yield a further reduction in CV risk, as optimal risk reduction occurs below the typical training volume of athletes[3].

4.4 Troponin release

Due to the presence of cardiac-specific isoforms, assessment of circulating cardiac troponins (cTn, either subunit I (cTnI) or T (cTnT) is currently the gold standard to assess myocardial injury in clinical practice[143], defined as a cTn value above the 99th percentile upper reference limit (URL). Acute or chronically elevated cTn concentrations are associated with a higher event rate in patients [144,145] and the general population[146].

Exercise is known to produce elevated cTn concentrations. A recent meta-analysis among 7,289 athletes from 129 studies has shown that 36% of athletes demonstrated cTn concentrations above the URL following exercise, with extreme between-study heterogeneity (range 2–98%)[147]. Post-exercise cTn elevations >URL were more common with high-sensitivity and cTnT assays, in middle-aged athletes, and after 3-6 hours of endurance exercise. Importantly, sex and training status did not impact cTn elevations. The onset of exercise-induced cTn elevations already occurs during the exercise bout[149], while complete normalization to resting concentrations typically occurs within 24-72 hours post-exercise[150]. Hence, the kinetics of exercise-induced cTn release are different from clinical scenarios such as a patient with an acute myocardial infarction[151].

The magnitude of exercise-induced cTn release is highly variable among athletes[14]. At least 10 factors have been identified as predictors of the magnitude of post-exercise cTn concentrations, with exercise intensity and exercise duration being listed as the greatest contributors[152,153]. Nevertheless, the predictive capacity of these combined predictors remains low, indicating that other unknown factors play an important role[148].

The high prevalence and large inter-individual variability of exercise-induced cTn elevations has raised questions on the clinical implications of these observations. A cross-sectional study linked the presence of occult coronary artery disease to abnormal cTn release patterns, predominantly a delayed recovery to normal kinetics[155]. However, a recent large study did not find a difference in the prevalence and magnitude of coronary atherosclerosis between recreational athletes with very high *versus* low post-exercise cTn concentrations[156]. Also, a well-controlled laboratory study did not find differences in exercise-induced elevations in cTn concentrations between athletes with *versus* without coronary artery disease [149]. These findings indicate that the interindividual variation in post-exercise cTn concentrations is unlikely attributable to occult coronary artery disease.

Prospective studies, linking post-exercise cTn concentrations to adverse health outcomes are scarce. A study among older long-distance walkers found that post-exercise cTnI concentrations above the URL were associated with an increased risk for all-cause mortality and major adverse cardiovascular events [157]. In contrast, no associations between elevated post-exercise cTnI concentrations and the incidence of adverse events[158] or cardiac dysfunction[159] were observed in German marathon runners during long-term follow-up. These contradictory findings indicate that elevated post-exercise cTn concentrations may hold prognostic value, but confirmation in larger, younger and more athletic cohorts is warranted to establish whether these outcomes can be extrapolated to the larger athletic community. The 10-year clinical outcomes of preregistered prospective cohort studies are, therefore, eagerly anticipated[153,160].

The underlying mechanisms of exercise-induced cTn elevations remain unknown. Previous studies showed that it may have a pathologic (i.e. necrosis or apoptosis) or physiologic origin (i.e. increased cardiomyocyte permeability or turnover), or a combination thereof[148]. For example, marathon running compromised cardiomyocyte integrity[161] which may allow cytosolic cTn fragments to leak from the cell into the circulation[162]. On the other hand, a recent MRI study showed no evidence to support the notion that first-time marathon running in healthy middle-aged men has a detrimental impact on the heart[163]. Further *in-vitro* and *in-vivo* studies are needed to establish the underpinnings of the physiological *versus* pathological nature of exercise-induced cTn elevations in athletes.

As a final note, it is noteworthy that exercise produces elevations in other biomarkers, including NTproBNP. Nevertheless, exercise-induced elevations in NTproBNP are generally mild, of temporal nature, and do often not cause clinical confusion[14].

4.5 Aortic dilatation

Aortic dilatation in young athletes is rare, but appears more frequently in master athletes and retired athletes, potentially linked to specific sport disciplines. In young (elite) athletes, aortic diameters are modestly larger than controls (~2-3mm sinus of valsalva, ~1-2mm aortic valve annulus)[164,165] , yet rarely exceed sex-specific or absolute cut-offs (prevalence 0.2 to 4.2%)[164–169]. These differences diminish after indexing for height, body surface area[165], and ventricular size [65,170,171], supporting the concept that mild aortic dilatation in this group reflects physiological remodeling rather than aneurysmal pathology. Longitudinal studies reinforce this interpretation, reporting slow annual growth (typically maximum 0.2–0.5 mm/year), well below clinically relevant thresholds – and an absence of major aortic events[167,169]. In contrast, up to 30% of master or retired athletes show aortic dilatation[172]. This appears associated with hypertension, exercise-induced hypertension[173,174], and specific sports (e.g. rowing, rugby, American-style football)[172,175,176]. Despite no robust data on longitudinal cohorts are available, reported growth rates appear modest, with a very low incidence of major aortic events[177].

Endurance disciplines, characterized by isotonic load, are associated with modest but consistent aortic root dilation compared with strength athletes and non-athletic controls[178]. Strength athletes, exposed predominantly to isometric load, may experience localized aortic wall stress, but without consistent evidence of dilation[164,169,178,179]. Sports with predominant isotonic components have been associated with greater aortic dimensions than predominantly isometric activities[179], although these differences often diminish after indexation and rarely exceed physiological limits[165,178]. Large meta-analyses involving over five thousand athletes further demonstrated that those engaged in predominantly isotonic training exhibited larger aortic roots than their isometric-trained counterparts; however, the magnitude of this increase was minor and

clinically insignificant[164,165]. In contrast, in master athletes, a clinically relevant prevalence of aortic dilatation has been reported in up to 20–25%. This prevalence was the highest in athletes with both isotonic and isometric loading (e.g. rowers)[172]. Overall, predominantly endurance sports may confer a slightly higher long-term risk of aortic dilatation, while more research is needed on aortic dilatation in combined endurance and strength disciplines in master athletes.

Table 2 and figure 3 summarizes the available evidence on the relationship between prolonged intense training and adverse structural remodelling as well as response to detraining.

5. Gender and ethnic differences: what are the main knowledge gaps?

Although exercise-induced cardiac remodelling has been studied for decades, our understanding of how these changes differ by sex and ethnicity remains limited[180–182]. Most research has focused on male, Caucasian, endurance athletes, which makes it difficult to apply the findings to women or athletes from diverse backgrounds. This leaves potentially important variations underexplored.

5.1 Sex differences

As previously discussed, men consistently show higher rates of sinus bradycardia, conduction abnormalities, pacemaker implantation, AF, non-sustained ventricular arrhythmias, myocardial fibrosis and coronary atherosclerosis compared with women. AF is particularly sex-specific: master male endurance athletes have a higher risk, while an increased incidence has not been demonstrated in female athletes [43]. In addition, one study found that highly trained men had more

bradycardia and were more likely to require pacemaker implantation whereas female skiers showed no such associations[31].

Similar to men, training in women induces significant electrical and structural adaptation[180]. However, compared to men, female athletes have smaller atrial and ventricular dimensions for their age, less cardiomyocyte hypertrophy, and milder exercise-induced bradycardia, all of which reduce the arrhythmogenic substrate. Female athletes also have lower resting and peak exercise blood pressures, contributing to fewer conduction abnormalities and atrial remodelling. Interestingly, the arrhythmic triggers such as premature atrial or ventricular beats appear similar between sexes, suggesting that it is the structural and electrophysiological environment, rather than trigger frequency, that drives the difference in arrhythmic risk[65,183,184].

Sex differences are probably shaped by hormonal, autonomic, and ion channel factors. Women generally have a higher sinoatrial node automaticity, lower sympathetic activity, and oestrogen-related cardioprotection, whereas testosterone and lower oestrogen states in men may promote hypertrophy and arrhythmogenesis[65,181]. Despite these insights, female athletes remain underrepresented in longitudinal studies, leaving important gaps in understanding how arrhythmias develop and progress over time and how cumulative exercise exposure affects these risks[185].

5.2 Ethnic differences

Evidence regarding ethnic variations in exercise-induced cardiac adaptations is even more limited. Most studies involve White athletes, with minimal representation from Black, Asian, or other minority groups. Ethnic differences in ECG patterns, repolarization, QT interval,

autonomic function, and sudden cardiac death risk are well established in the general population[17,182]. However, whether these translate into differential arrhythmic susceptibility in athletes is largely unknown. Interactions between ethnicity, sex, and genetic predisposition for conduction disease, atrial or ventricular arrhythmias, and cardiomyopathies remain largely unexamined.

6. Clinical impact of sport-related chronic adverse cardiovascular effects

As discussed, observational studies have reported structural and electrical findings such as focal myocardial fibrosis, increased coronary artery calcification, and a higher prevalence of AF among endurance athletes compared with sedentary individuals. These observations have prompted debate over whether long-term, high-intensity and volume exercise might predispose some athletes to adverse cardiovascular outcomes later in life[57]. However, the clinical significance, causality, reversibility, and long-term prognostic implications of these observations remain incompletely understood. In particular, the extent to which exercise itself contributes to these changes, as opposed to unmasking or interacting with individual susceptibility, remains uncertain. The generalizability of these observations also remains uncertain, as the available evidence is derived predominantly from cohorts of Caucasian male endurance athletes.

A central theme in this discussion is the so-called "mortality paradox". Despite imaging or arrhythmic findings that could be interpreted as maladaptive, large-scale cohort studies consistently show that former elite athletes enjoy equal or greater longevity than the general population and that extreme doses of exercise do not increase the risk of adverse outcomes[186–193]. A striking example is the recent analysis of the first 200 men to run a sub-4-minute mile, who lived an average of 4.7 years longer than expected for age, sex, country and birth cohort,

supporting the concept that even extreme levels of aerobic training are compatible with exceptional longevity[194]. These data suggest that any potential structural or arrhythmic risks associated with lifelong athletic training do not outweigh the benefits of physical activity, even if intense, at a population level.

For example, AF is one of the most reproducible associations between endurance exercise and cardiac remodelling. However, some observational studies suggest that athletes with AF may have a lower stroke risk profile than non-athletic AF populations, although AF in athletes remains associated with an increased stroke risk compared with athletes without AF[38,43]. CAC is also more frequently identified in veteran endurance athletes but this does not seem to translate into increased risk of clinical coronary events. A possible explanation is that in most studies, coronary plaques tend to be stable and heavily calcified, implying a lower propensity for rupture compared with the mixed or lipid-rich plaques seen in sedentary individuals[141,195]. Finally, small areas of non-ischemic myocardial fibrosis are common in master athletes and associated to premature ventricular beats but their clinical meaning remain to be established[196].

However, these observations must be interpreted with appropriate caution. Lifelong athletes likely represent a highly selected population enriched for favourable genetic, behavioural, and socioeconomic characteristics that may independently confer protection against cardiovascular disease. Healthy behaviours and lifestyle after retirement likely contribute importantly to these outcomes. In addition, athletes undergo repeated medical evaluations throughout their careers, which may increase the likelihood of identifying and excluding individuals with occult cardiovascular disease. Thus, the observed mortality benefit may reflect, at least in part, **genetic and biological resilience, healthier lifestyles, and repeated medical screening, all of which may both enable sustained athletic participation and contribute to improved long-term**

outcomes. This selection effect, often referred to collectively as the "healthy athlete effect", complicates direct causal inference regarding the long-term clinical impact of sport-related chronic adverse cardiovascular effects.

7. Conclusions

In conclusion, the available evidence suggests that while long-term participation in intensive sport is safe for most athletes and generally associated with favourable health and survival outcomes, in some athletes is may be associated with features of cumulative cardiovascular stress. These observations support the concept that chronic, high-volume exercise loads may, in susceptible subjects, contribute to structural, electrical and vascular remodelling beyond the traditionally recognized physiological spectrum (Figure 4)[196]

Current evidence remains largely observational, and important uncertainties persist regarding causality, dose–response relationships, reversibility, and the contribution of genetic or acquired susceptibility factors. In particular, no uniform threshold of "excessive" exercise above which cardiovascular risk consistently increases can be identified. A major limitation is that most data derive from studies conducted in male, predominantly Caucasian endurance athletes. Evidence regarding female athletes and individuals from other ethnic backgrounds is scarce or lacking, despite well-recognized sex- and ethnicity-related differences in cardiovascular structure, adaptation and disease expression. Addressing these gaps represents a key priority for future research.

The observations discussed in the manuscript should not be dismissed as clinically irrelevant, because in selected athletes they may identify early disease expression, increased susceptibility, or a subgroup requiring closer clinical evaluation and longitudinal follow-up. However, any

discussion of potential adverse cardiovascular adaptations should be interpreted within the broader context of the well-established cardiovascular and overall health benefits associated with regular physical activity compared with sedentary behaviour. The goal should therefore not be to discourage exercise, but rather to promote a more individualized approach to training, cardiovascular evaluation, and longitudinal follow-up, particularly in ageing athletes and in those with markers of increased susceptibility. In this context, sports cardiology plays a central role in guiding athletes across their life course.

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Table 1 – Summary of evidence of an association between high cumulative sport dose and electrical abnormalities, reversibility with detraining and implications for athletes.

	Sinus or AV node dysfunction
Evidence of an association:	Emerging evidence of an association between persistent sinus node dysfunction or advanced/complete atrioventricular and long-life intense endurance sports activity in former male athletes. No evidence in female athletes.
Type of studies	Cross-sectional observational, retrospective observational, longitudinal cohort (long-term follow-up and population-based)
Frequency and comparison with controls	Endurance athletes may exhibit a modestly increased long-term risk of sinus node dysfunction and pacemaker implantation compared with controls (relative risk increase approximately 15–20% in large cohort studies), particularly in male athletes with high cumulative training exposure.
Reversibility with detraining:	Although sinus bradycardia and first degree/second degree Mobitz type 1 atrioventricular block usually improve or disappear with detraining, there is evidence that sinus node and atrioventricular node function may not

	completely normalize, possibly reflecting intrinsic sinus node remodeling and only partial reversibility.
Implications for athletes:	A minority of master or former athletes may require a pacemaker implantation at a younger age than non-athletes, with no impact on mortality.
	Atrial Fibrillation
Evidence of an association:	There is strong evidence of an association between atrial fibrillation and master endurance male athletes. Limited evidence in female athletes.
Type of studies	Observational studies **(**large population-based cohorts, matched cohort studies, case-control studies, cross-sectional imaging/mechanistic studies, retrospective/registry-based studies, prospective and longitudinal cohort studies), reviews and scoping/umbrella reviews
Frequency and comparison with controls	In comparisons with sedentary controls, matched general-population controls, or lower-exposure athletes, endurance athletes tend to show a higher prevalence and/or incidence of AF (2-5 fold). However, former athletes did not show an increased risk of stroke.
Reversibility with detraining:	Detraining may reduce the overall burden of atrial fibrillation, though studies to address the effect of such intervention are still lacking.
Implications for athletes:	Management should be individualized through shared decision-making, considering symptoms, AF pattern, sport type, treatment strategy, anticoagulation, and structural heart disease. Reduction of training intensity or volume may be considered in selected endurance athletes, but the optimal degree of reduction remains undefined. Significant physiological

	remodelling of the sinus node and atrioventricular node often leads to intolerance to drug therapy, which is why athletes are often referred for ablative procedures instead.
	Premature ventricular beats
Evidence of an association:	Overall weak and inconsistent evidence: most athletes show a low premature ventricular beats (PVBs) burden, with a possible increase only in a minority of endurance senior athletes.
Reversibility with detraining:	Detraining may reduce PVB burden in some athletes, but spontaneous variability and lack of a clear cause–effect relationship limit definitive conclusions.
Type of studies	Cross-sectional Holter studies; limited longitudinal/detraining data.
Frequency and comparison with controls	Low burden in most athletes; >100 PVBs/day in a minority (5–15%), with higher prevalence in older than younger athletes and inconsistent differences versus controls.
Implications for athletes:	Although PVBs are usually a benign finding in athletes, they should be investigated to rule-out the presence of an underlying structural heart disease or metabolic disturbance.
	Exercise-induced Long QT
Evidence of an association:	Although average QTc interval in athletes is similar or just slightly prolonged compared to sedentary individuals, a small minority of athletes show significant QT prolongation in the absence of genetic disease.

Type of studies	Cross-sectional ECG studies; small detraining cohorts; limited longitudinal data.
Frequency and comparison with controls	Rare finding; clearly prolonged QTc reported in <1% of athletes in large cohorts, with uncertain excess versus controls.
Reversibility with detraining:	QT prolongation may normalize after detraining in athletes with long-QT but negative genetic testing and family history, with recurrence after resumption of intensive training only in some of them.
Implications for athletes:	There is no evidence about the arrhythmic risk attributable to an exercise-induced long QT phenotype in athletes without underlying genetic or structural heart disease. Therefore, management of these athletes remain equivocal.

Table 2 – Summary of evidence of an association between high cumulative sport dose and structural cardiovascular abnormalities/troponin release, reversibility with detraining and implications for athletes.

	Exercise-induced arrhythmogenic cardiomyopathy phenotype
Evidence of an association:	Moderate evidence supports an association between long-term high-intensity endurance exercise and the development of an exercise-associated arrhythmogenic RV phenotype in a small subset of susceptible athletes, even in the absence of identifiable desmosomal gene mutations.
Type of studies	Observational cohort and case-control studies in endurance athletes with ventricular arrhythmias, electrophysiological substrate mapping studies,

	advanced imaging studies demonstrating localized RV scar, and genotype-positive/genotype-negative arrhythmogenic cardiomyopathy cohorts showing exercise-related disease acceleration.
Frequency and comparison with controls	Compared with non-athletic controls, endurance athletes presenting with complex ventricular arrhythmias demonstrate a higher prevalence of RV structural, functional, and electrophysiological abnormalities, including localized RV scar and impaired RV function. However, the true prevalence (possibly <1%) in the general athletic population remains uncertain because most studies are referral-based and include highly selected athlete cohorts. In contrast, isolated RV enlargement is common in endurance athletes and frequently represents physiological remodeling.
Reversibility with detraining:	Detraining is associated with a reduction in arrhythmic burden and disease progression, although complete reversal of structural or functional abnormalities is uncommon.
Implications for athletes:	The exercise-induced arrhythmogenic cardiomyopathy phenotype may present with ventricular arrhythmias that mimic benign right ventricular outflow tract arrhythmias, requiring careful differential diagnostic evaluation. Importantly, isolated right ventricular enlargement in athletes should not be considered diagnostic of cardiomyopathy in the absence of accompanying arrhythmic, functional, or structural abnormalities suggestive of arrhythmogenic disease. Exercise restriction represents a cornerstone of management, while catheter ablation or ICD implantation may be considered in selected high-risk individuals.

	Non-ischemic left ventricular fibrosis
Evidence of an association:	No definitive evidence demonstrating a causal association between sport participation and myocardial fibrosis as suggested by late gadolinium enhancement (LGE). Some cohorts show a higher prevalence in master endurance athletes compared with controls.
Type of studies	CMR studies mainly in middle-aged endurance athletes; limited longitudinal/outcome data.
Frequency and comparison with controls	Highly variable prevalence, from <5% to ~50%, depending on LGE definition, inclusion of hinge-point LGE, and CMR methods; generally reported as more frequent than in controls.
Reversibility with detraining:	Myocardial fibrosis is not reversible. However, other causes of LGE (such as myocardial edema) are potentially reversible. There are no longitudinal studies assessing reversibility of LGE with detraining
Implications for athletes:	Management depends on the clinical context, including the presence of ventricular arrhythmias, extent and pattern of LGE, and symptoms. Right ventricular hinge-point LGE is considered a benign finding and is not associated with adverse prognosis.
	Coronary atherosclerosis
Evidence of an association:	Positive association between exercise intensity/volume and coronary atherosclerosis in middle-aged and older male athletes. Exercise characteristics were not related with coronary atherosclerosis in female athletes.

Type of studies	Cross-sectional and longitudinal CT studies, mainly in middle-aged male endurance athletes.
Frequency and comparison with controls	Coronary artery calcification/plaque burden is often higher than in controls; prevalence of coronary plaques ranges widely, approximately ~30–70% in master athletes varies widely by age, risk profile, and exercise exposure. High-risk plaque features appear uncommon.
Reversibility with detraining:	Coronary artery calcification is non-reversible. No evidence available on detraining effect on non-calcified plaques.
Implications for athletes:	Increased coronary atherosclerosis does not seem to cause an increased risk of coronary events. At present, there is no evidence to support changing exercise training patterns in asymptomatic athletes with non-obstructive coronary atherosclerosis. Cardiovascular risk factor management is also important in athletes and should be managed according to general population guidelines.
	Cardiac troponin elevations
Evidence of an association:	Positive associations between exercise-induced workload (i.e. exercise duration and exercise intensity) and post-exercise cardiac troponin concentrations.
Type of studies	Mostly acute exercise studies; meta-analyses; limited long-term outcome data.
Frequency and comparison with controls	Common after endurance exercise; recent meta-analysis reports cTn > upper reference limit in ~one third of athletes post-exercise, with wide variability by assay, exercise duration/intensity, and sampling time.

Reversibility with detraining:	Troponin concentrations show peak values at 3-6 hours post-exercise, with complete normalization within 24 to 72 hours following exercise cessation.
Implications for athletes:	Exercise-induced elevations of cardiac troponin concentrations are transient and common in athletes. Abnormal troponin concentrations are prognostic for adverse outcomes in older long-distance walkers, but it remains unclear whether these findings can be extrapolated to younger and low-risk athletes.
	Aortic dilatation
Evidence of an association:	Aortic dilation is uncommon in young athletes and generally reflects physiological remodelling, characterised by slow progression and no excess risk of adverse events. Prevalence is higher in master and retired athletes, particularly those engaged in endurance or mixed-load sports.
Type of studies	Echocardiographic and CMR/CT studies; mostly cross-sectional, with limited longitudinal data.
Frequency and comparison with controls	Rare in young athletes (<5%); more frequent in master/retired athletes (~20–30%), especially in endurance or mixed-load sports; usually mild, with low event rates.
Reversibility with detraining:	Data on reversibility is limited, but available evidence suggests that aortic dimensions in athletes tend to show slow progression rather than regression, and there is no evidence that detraining leads to a reduction of aortic size once dilatation is present.

Implications for athletes:	In young athletes, mild aortic enlargement is usually benign and rarely exceeds clinical thresholds. In contrast, in master athletes, periodic surveillance may be warranted due to a higher prevalence of clinically relevant dilatation despite low event rates.

FIGURES

Figure 1 - Electrical abnormalities associated with long-term training

Schematic summary of the main electrical adaptations and arrhythmic findings reported in athletes. The strength of evidence for an association with training and the degree of reversibility with detraining are qualitatively graded based on the available literature (0/3: no evidence; 1/3: low or preliminary evidence; 2/3: moderate evidence; 3/3: strong evidence).

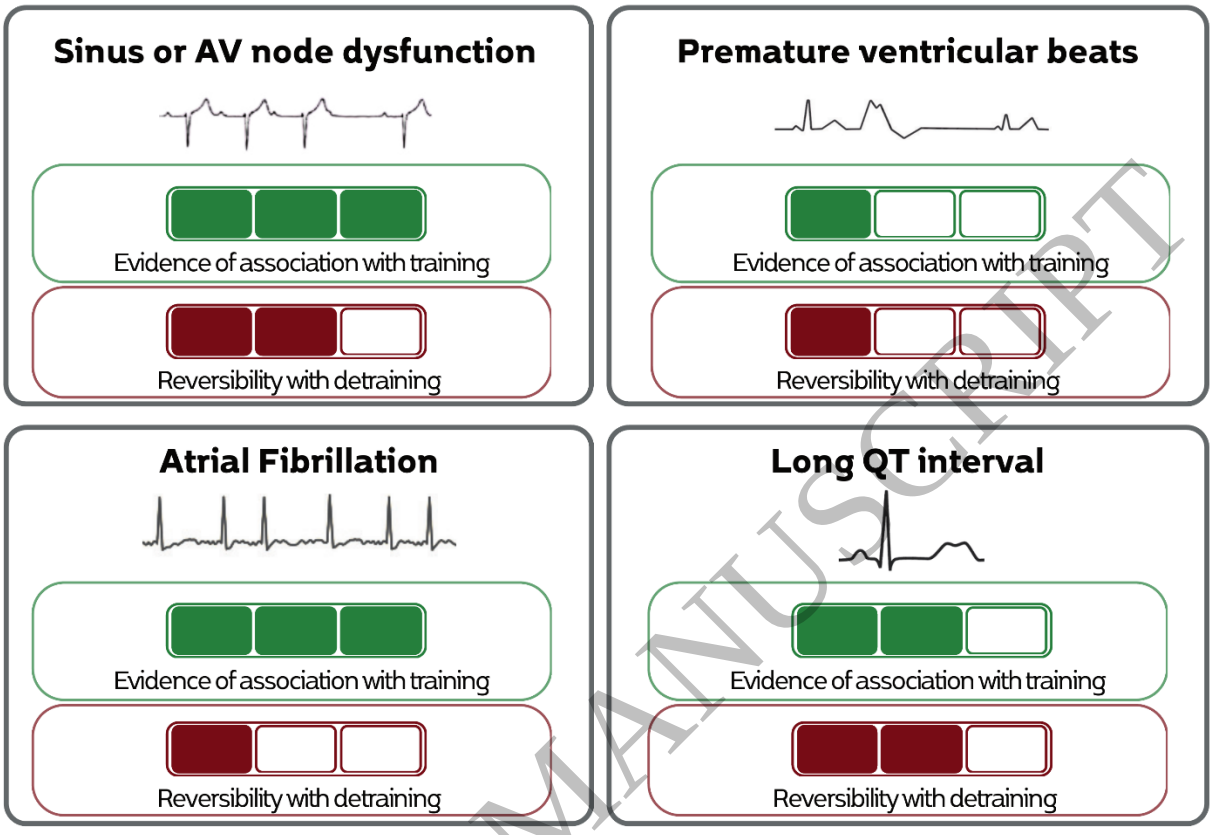

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Figure 2: Spectrum of arrhythmogenic cardiomyopathy expression and its relation to cumulative exercise exposure.

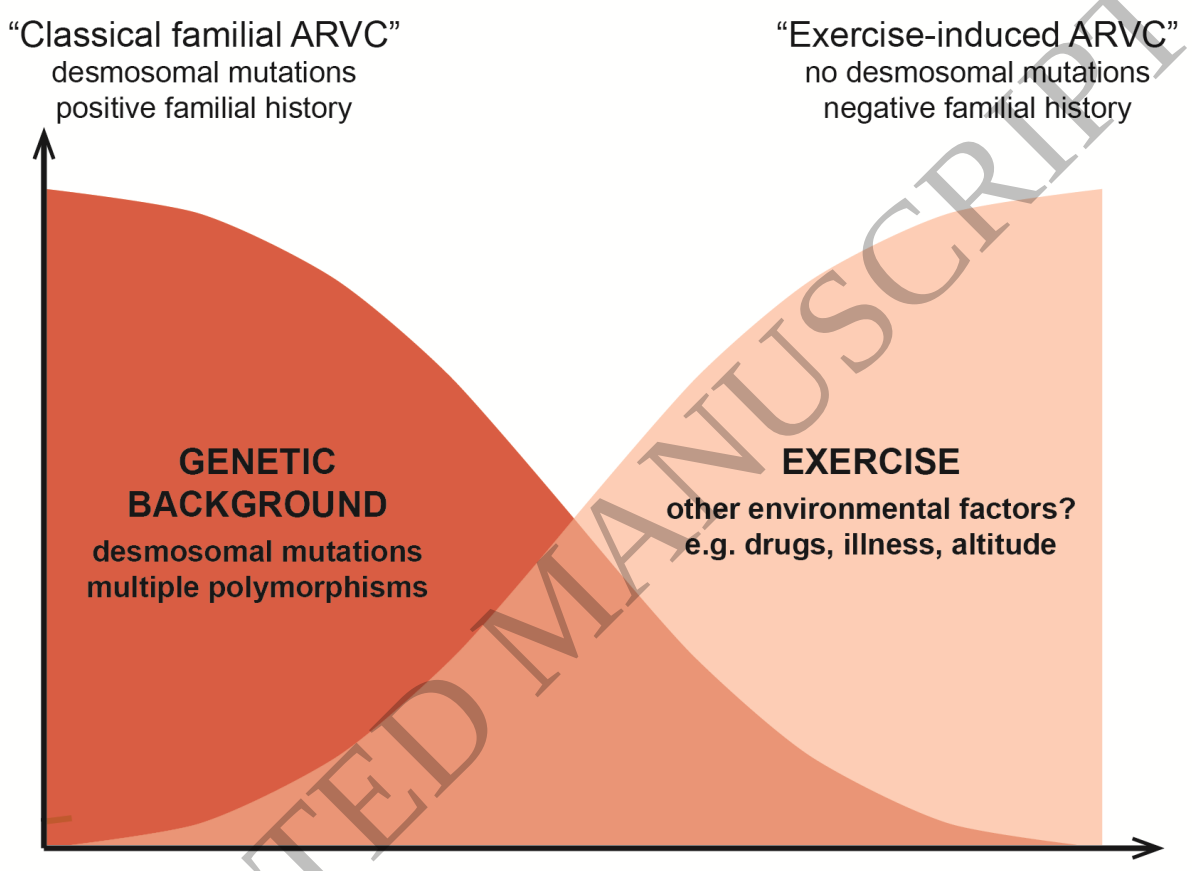

Figure 3 – Structural cardiovascular abnormalities associated with long-term training

Schematic summary of the main myocardial and vascular abnormalities reported in athletes. The strength of evidence for an association with training and the degree of reversibility with detraining are qualitatively graded based on the available literature (0/3: no evidence; 1/3: low or preliminary evidence; 2/3: moderate evidence; 3/3: strong evidence).

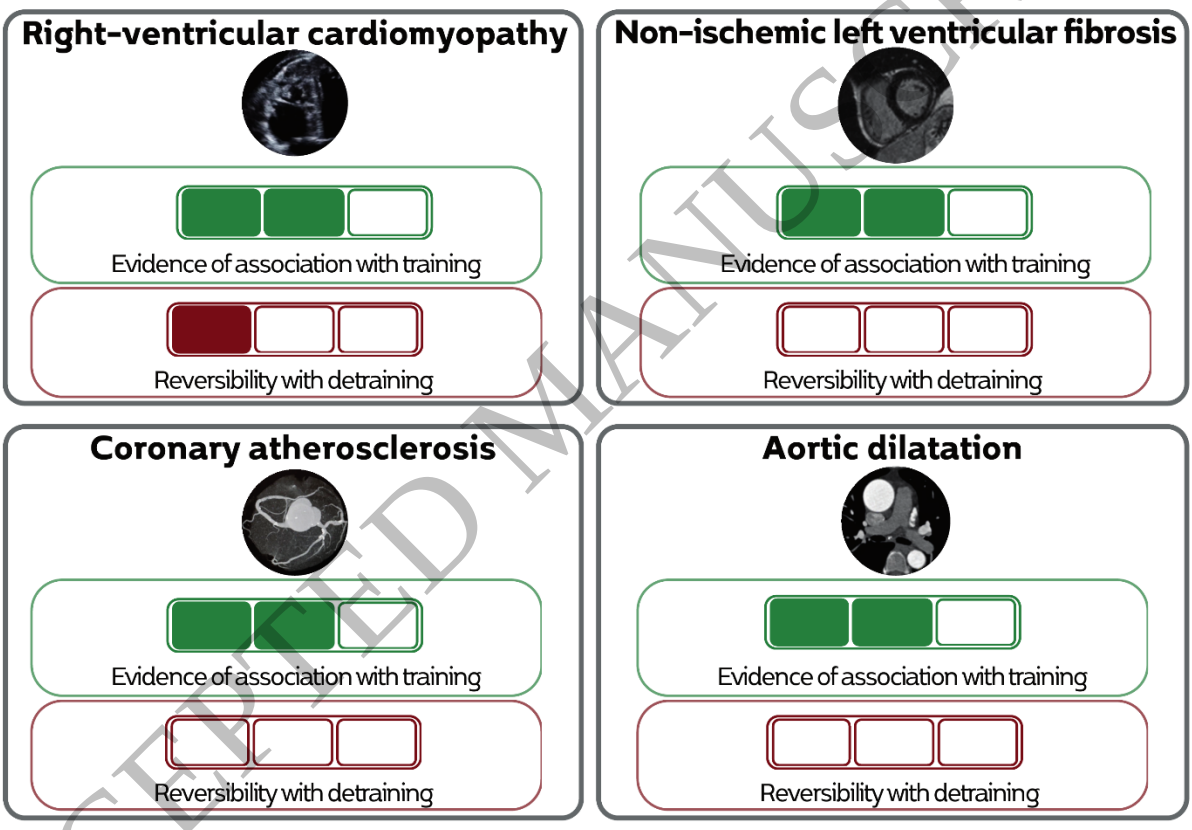

Figure 4: Conceptual visualization of the Extreme Exercise Hypothesis.

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